

# The Star Formation History of Ellipticals from the Fossil Evidence

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**Abstract.** The current evidence about the age of stellar populations in elliptical galaxies is reviewed. The case for the bulk of stars in galactic spheroids (ellipticals and bulges) having formed at high redshift ( $z \gtrsim 3$ ) is now compelling, both for cluster and well as field galaxies. Whether the assembly of ellipticals is deferred to lower redshifts compared to the formation of their stars remains controversial, and we mention ongoing observational programs that are designed to solve the issue. We present preliminary results of a pilot project aimed at ascertain the nature of extremely red galaxies (ERGs) with near-IR spectroscopy at the VLT.

## 1. The Age of Cluster Ellipticals

Through the '80s it became normal to start a talk about ellipticals by saying that 'the classical view of elliptical (and spheroid) formation was that they formed stars efficiently in the early universe, and then their stellar population evolved passively after this initial burst'. Then the talk would have continued by saying '... however, in recent years there has been growing evidence that this is not the true story, ellipticals are rather *intermediate age* objects, and star formation in them has continued for a major fraction of the Hubble time and in some cases is still going on today ...'. Actually, such evidence hardly grew, in spite of a widespread expectation given the success of hierarchical theories of structure formation coupled to the aesthetic appeal of  $\Omega = 1$  inflationary cosmology.

From the turn of the decade through all the '90s there has been instead growing empirical evidence that ellipticals are dominated by very old stellar populations. The first breakthrough came from noting the tightness of the color- $\sigma$  relation of ellipticals in the Virgo and Coma clusters (Bower, Lucey, & Ellis 1992). This demands a high degree of *synchronization* in the star formation history of these ellipticals, that is most naturally accounted for by pushing back to early times most of the star formation. Making minimal use of stellar population models, this approach provided for the first time a *robust* demonstration that at least *cluster* ellipticals are made of very old stars, with the bulk of them having formed at  $z \gtrsim 2$ .

The main lines of the Bower et al. argument are as follows. The observed color scatter of cluster ellipticals is related to the age dispersion among them by the relation:

$$\delta(U - V) = \frac{\partial(U - V)}{\partial t}(t_H - t_F) \quad (1)$$

where  $t_H$  and  $t_F$  are the age of the “oldest” and “youngest” galaxies, respectively. Here by age one intends the luminosity-weighted age of the stellar populations that constitute such galaxies. The time derivative of the color is obtained from evolutionary population synthesis models, which give  $\partial(U - V)/\partial t \simeq 0.02$  mag/Gyr for  $t \simeq 10$ . The observed color scatter is  $\delta(U - V) \simeq 0.04$  mag, consistent with pure observational errors. Hence, one gets  $t_H - t_F \lesssim 0.04/0.02 = 2$  Gyr, and if the oldest galaxies are 15 Gyr old, the youngest ones ought to be older than 13 Gyr, from which Bower et al. conclude they had to form at  $z \gtrsim 2$ . If the oldest galaxies were instead as young as, say 5 Gyr, then the youngest should be older than at least 3 Gyr, which would require a high degree of synchronization in their formation, which seems unlikely.

Evidence in support of the Bower et al. conclusion has greatly expanded, to finally become compelling. It is worth mentioning some of the steps of this development: the tightness of the fundamental plane relation for ellipticals in local clusters (Renzini & Ciotti 1993), the tightness of the color-magnitude relation for ellipticals in clusters up to  $z \sim 1$  (e.g., Aragon-Salamanca et al. 1993; Taylor et al. 1998; Kodama et al. 1998; Stanford, Eisenhardt, & Dickinson 1998), and the modest shift with increasing redshift in the zero-point of the fundamental plane,  $\text{Mg}-\sigma$ , and color-magnitude relations of cluster ellipticals (e.g., Bender et al. 1997; Dickinson 1995, 1997; Ellis et al. 1997; van Dokkum et al. 1998; Pahre, Djorgovski, & de Carvalho 1997; Stanford, et al. 1998; Kodama et al. 1998). All these studies agree in concluding that most stars in ellipticals formed at  $z \gtrsim 3$ , though the precise lower limit of the redshift depends on the adopted cosmology; it would be more like  $z \gtrsim 2$  in the current *standard* cosmology:  $(\Omega, \Lambda) = (0.3, 0.7)$ .

It is worth emphasizing that all these studies have in common the same methodology pioneered by Bower et al. (1992). They focus indeed on the tightness of some correlation among the global properties of cluster ellipticals, which sets a robust constraint on their age dispersion as opposed to an attempt to date individual galaxies. Moreover, the move to high redshift offers two fundamental advantages. The first advantage is that looking at high  $z$  provides the best possible way (we should say *the* way) of removing the age-metallicity degeneracy. If spheroids are made of intermediate-age, metal rich stars, they should become rapidly bluer and then disappear already at moderate redshift, which is not the case (e.g. Kodama & Arimoto 1997).

It has also been demonstrated that the scatter about the average  $\text{Mg}-\sigma$  relation (among local  $z \simeq 0$  cluster ellipticals) is larger than expected from pure observational errors (Colless et al. 1999). Colless et al. interpret this as evidence for a substantial age dispersion, but it remain to be seen whether this interpretation is consistent with the color scatter remaining constant all the way to  $z \simeq 1$ , as found by Stanford et al. (1998). The observational opportunity of studying galaxies at large lookback times makes quite obsolete those attempts to find combinations of spectral indices that are aimed at distinguishing between age and metallicity effects in nearby galaxies. The obvious drawback of these

indices (e.g.  $H_\beta$ ) is that they are very sensitive to even minor recent episodes of star formation, and therefore they do not help to determine the formation epoch for the *bulk* of stars in ellipticals.

The second advantage of high- $z$  studies is that at high redshift one gains more *leverage*: for given dispersion in some observable one can set tighter and tighter limits to the age dispersion. This comes from the color time derivatives being larger the younger the population. For example, the derivative  $\partial(U-V)/\partial t$  is  $\sim 7$  times larger at  $t = 2.5$  Gyr than it is at  $t = 12.5$  Gyr (e.g. Maraston 1998), and therefore a given dispersion in this rest-frame color translates into a  $\sim 7$  times tighter constraint on age and therefore on formation redshift. The case is effectively illustrated by isolated high redshift ellipticals: Spinrad et al. (1997) found a *fossil* (i.e. passively evolving) elliptical at  $z = 1.55$  for which they infer an age of at least 3.5 Gyr, hence a formation redshift in excess of  $\sim 5$ . A similar case is anticipated by Dunlop (1998), with a galaxy at  $z = 1.43$  and an age of 3-4 Gyr. At an even higher formation redshift may lie the extremely red galaxy in the NICMOS field of the HDF-South, which spectral energy distribution is best accounted for by an old, passively evolving population at  $z \simeq 2$  (Stiavelli et al. 1999).

## 2. Cluster vs Field Ellipticals

Most of the evidence mentioned in the previous Section refers to cluster ellipticals. In hierarchical models, clusters form out of the highest peaks in the primordial density fluctuations, and cluster ellipticals completing most of their star formation at high redshifts could be accommodated in the model (e.g. Kauffmann 1996; Kauffmann & Charlot 1998a). However, these models predict that in lower density, *field* environments, both star formation and merging should be appreciably delayed to later times, which offers the opportunity for an observational test of the hierarchical merger paradigm.

The notion of field ellipticals being a less homogeneous family compared to their cluster counterparts has been widely entertained, though – once more – the direct evidence has been only rarely discussed. Visvanathan & Sandage (1977) found cluster and field ellipticals to follow the same color-magnitude relation, but Larson, Tinsley, & Caldwell (1980) – using the same database – concluded that the scatter about the mean relation is larger in the field than in clusters. More recently, a larger scatter in field versus cluster ellipticals was also found for the fundamental plane relations by de Carvalho & Djorgovski (1992). However, when using absolute luminosities and effective radii at least part of the larger scatter among field ellipticals certainly comes from their distances being more uncertain than for cluster galaxies.

Taking advantage of a large sample ( $\sim 1000$ ) of early-type galaxies with homogeneously determined  $M_{g_2}$  index and central velocity dispersion, Bernardi et al. (1998) have recently compared the  $M_{g_2} - \sigma$  relations (which are distance independent!) of cluster and field galaxies. The result is that field and cluster ellipticals all follow basically the same  $M_{g_2} - \sigma$  relation. The zero-point offset between cluster and field galaxies is  $0.007 \pm 0.002$  mag, with field galaxies having lower values of  $M_{g_2}$ , a statistically significant, yet very small difference. This is in

excellent agreement with the offset of  $0.009 \pm 0.002$  mag, obtained by Jorgensen (1997) using 100 field and 143 cluster galaxies.

Using the time derivative of the  $Mg_2$  index from synthetic stellar populations, Bernardi et al. conclude that the age difference between the stellar populations of cluster and field early-type galaxies is at most  $\sim 1$  Gyr. The actual difference in the mass-weighted age (as opposed to the luminosity-weighted age) could be significantly smaller than this. It suffices that a few galaxies have undergone a minor star formation event some Gyr ago, with this having taken place preferentially among field galaxies.

### 3. Spiral Galaxy Bulges

According to general wisdom, the bulges of spiral galaxies are hard to distinguish from elliptical galaxies of the same luminosity, once they are stripped of the disk which rotates around them. This is illustrated for example by most bulges following the same  $Mg_2 - \sigma$  and  $Mg_2$ -luminosity relation as common ellipticals (Jablonka, Martin, & Arimoto 1996). In their sample just  $\sim 20\%$  of the studied bulges appear to be appreciably bluer than the standard relation for ellipticals, a sign that recent star formation is required in only a minority of the bulges.

Closer to us, contrary to several early claims, no evidence exists for an intermediate age population for the bulge of M31 (e.g. Renzini 1998; 1999; Jablonka et al. 1999). Even more stringently, HST and ground based color-magnitude diagrams of Galactic bulge globular clusters and fields indicate a uniform old age for our own bulge (Ortolani et al. 1995). Given that we live in a galaxy that is member of a rather loose group, certainly not an exceptionally high peak in the primordial density fluctuations, it seems reasonable to conclude that star formation in most galactic spheroids, ellipticals and bulges alike, was essentially complete at high redshift, no matter whether such spheroids reside today in high- or low-density environments.

### 4. Do Ellipticals Disappear by $z \simeq 1$ ?

In apparent conflict with this conclusion are several claims according to which the comoving number density of field elliptical galaxies is rapidly decreasing with redshift by  $z \simeq 1$  (e.g. Kauffmann, Charlot, & White 1996; Zepf 1997; Meneanteau et al. 1998; Franceschini et al. 1998). This is a controversial result. Other groups claim such dismissal of high-redshift ellipticals to be premature, either because the adopted models for putative high- $z$  ellipticals would be too naive (Jimenez et al. 1999), or because they find evidence for the comoving number density of ellipticals being constant to at least  $z \sim 1$  (e.g. Totani & Yoshii 1998; Benitez et al. 1998; Shade et al. 1999), and possibly as much as to  $z \sim 2$  (Broadhurst & Bouwens 1999).

Part of this discrepancy is likely to arise from the samples so far analyzed being rather small, both in terms of the total number of galaxies involved, and especially in terms of the (small) number of large scale structures that happen to be included in each sample (see below). Part of the discrepancy may also arise from the use of different selection criteria for ellipticals. Clearly, these differences need to be understood before claiming evidence in support of a late

assembly of ellipticals (as favored by most current realization of the CDM model of hierarchical formation of cosmic structures, e.g. Kauffmann & Charlot 1998a), or in support of an early build-up of massive galaxies, resembling the “old-fashioned” monolithic collapse models.

## 5. Searching for Fossil Ellipticals at High $z$ : Early VLT Observations of Extremely Red Galaxies

The existence and the abundance of fossil ellipticals at  $z > 1$  can be constrained with the selection and study of faint galaxies with the colors expected for passively evolving old stellar populations. For instance, a color threshold of  $R-K \gtrsim 5.3$  is expected at  $z \gtrsim 1$  in the case of a passively evolving, solar metallicity stellar population with  $z_{\text{form}} > 3$ ,  $SFR \propto \exp(-t/\tau)$  and  $\tau=0.1$  Gyr (adopting the Bruzual & Charlot 1998 models, and assuming  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $\Omega_0 = 1$ ). The observed colors of the few known isolated  $z > 1$  ellipticals (see Section 1) are indeed consistent with those expected from the spectral synthesis models.

Do such color-candidate ellipticals at  $z > 1$  exist? Observationally, the answer is yes: a population of extremely red galaxies (hereafter ERGs) was discovered with the combination of optical and near-IR imaging (e.g. Elston et al. 1988; McCarthy et al. 1992; Hu & Ridgway 1994). ERGs are ubiquitously found in empty sky fields (Cohen et al. 1999; Thompson et al. 1999), in the vicinity of high- $z$  AGN (McCarthy et al. 1992; Hu & Ridgway 1994) and as counterparts of faint X-ray (Newsam et al. 1997) and weak radio sources (Spinrad et al. 1997). Their typical magnitudes  $K \sim 18 - 20$ , and their surface density for  $R - K > 6$  and  $K < 19$  is  $0.039 \pm 0.016$  ERGs/sq. arcmin (Thompson et al. 1999). Their nature is still poorly known, as their faintness makes optical and near-IR spectroscopic observations quite difficult, but they are likely to represent a *mixed bag* class of objects. Indeed, their red colors are consistent with them being passively evolving ellipticals, but also with strong dust reddening in a star-forming or active galaxy. A dramatic example of this ambiguity is provided by HR10: its spectral energy distribution (SED) is consistent with that of an old elliptical at  $z \approx 2.4$  (Hu & Ridgway 1994), but near-IR and submm observations proved that HR10 is a dusty starburst galaxy at  $z = 1.44$  (Graham & Dey 1996; Cimatti et al. 1998; Dey et al. 1999). On the other hand, recent observations suggest that the ERG CL 0939+4713B ( $R - K \sim 7$ ) is an old galaxy at  $z \sim 1.6$ , based on the detection of the redshifted 4000 Å break (Soifer et al. 1999).

In order to investigate the nature of ERGs and their role in the framework of elliptical galaxy formation and evolution, we recently started a project based on optical and near-IR imaging and spectroscopy with the ESO NTT 3.5m and the VLT 8m telescopes. Near-infrared ( $JHK$ ) spectroscopy of an incomplete “pilot” sample of ERGs was made in April 1999 with the ESO VLT-UT1 (*Antu*) equipped with the IR imager-spectrograph ISAAC (Moorwood et al. 1999). The typical integration times were 1-2 hours per spectrum and the resolution was  $\sim 500$ . Nine ERGs with  $R - K > 5$  or  $I - K > 4.5$  were observed with the main purpose of finding cases of *bona fide* ellipticals at  $z > 1$  or, in case of dusty starburst/active galaxies, to search for redshifted emission lines (such as  $H\alpha$  at  $z > 0.7$ ) (Cimatti et al. 1999).

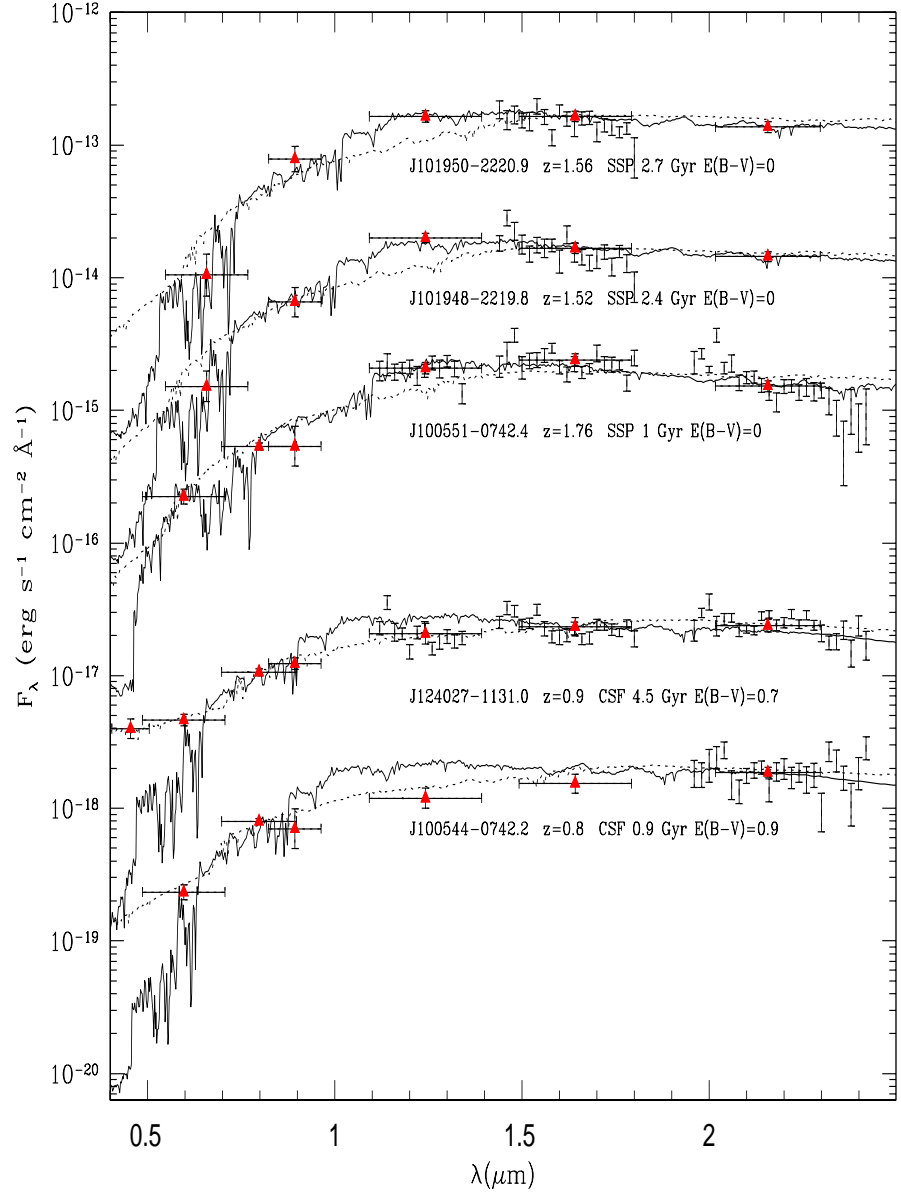


Figure 1. The optical to near-IR SEDs of five ERGs from broad-band photometry (filled triangles) and ISAAC near-IR spectroscopy (vertical bars). The spectra are binned with 200 Å wide bins in order to reach a typical  $S/N \approx 10$  per bin. The first three SEDs from the top are those consistent with both passively evolving ellipticals and no dust extinction. Instead, the other two SEDs require substantial dust extinction to be reproduced. The continuum and the dotted lines are the best fit spectra obtained respectively with dustless, old stellar populations and with dust-obscured constant star formation. The best fit parameters ( $z$ , ages and  $E_{B-V}$ ) are shown relatively to the best fit of the two cases (i.e. dusty or dustless). From bottom to top, the fluxes of the five SEDs are multiplied by  $10^0, 1, 2, 4, 5$  respectively.

Continuum emission was detected in all the targets, but neither strong emission lines nor evident continuum breaks were detected in the ISAAC spectra. The depth of our spectra (typically  $F_{\text{lim}} < 2 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ ) would allow to detect emission lines such as  $\text{H}\alpha$  if as strong as in HR10 (Dey et al. 1999). These limits on the  $\text{H}\alpha$  emission imply upper limits on the star formation rates of individual galaxies that – in absence of dust extinction – range from  $\sim 7$  to  $\sim 30 h_{50}^{-2} \text{ M}_{\odot} \text{ yr}^{-1}$  ( $\Omega_0 = 1.0$ ). These limits correspond to the SFRs as high as those of nearby gas rich spiral galaxies (Kennicutt 1998). However, in case of strong dust extinction, the SFRs would increase significantly. For instance, adopting the Calzetti (1997) extinction curve, for  $E_{B-V} = 0.2\text{--}0.9$ , the corresponding correction factors of the *SFR* (as derived from  $\text{H}\alpha$ ) are  $\approx 2\text{--}30\times$ .

In absence of distinctive spectral features, the ISAAC spectrophotometry combined with the available optical and near-IR broad-band photometry was used to estimate the “spectrophotometric” redshifts of the observed ERGs and to study their SEDs. We found that a fraction of the program ERGs have SEDs consistent with being passively evolving ellipticals at  $z \sim 1.5\text{--}1.8$  with no dust extinction and rather old ages ( $\sim 1\text{--}3 \text{ Gyr}$ ) (see Fig. 1). Their rest-frame *K*-band absolute magnitudes ( $M_K \sim -24.8\text{--}-25.2$ ) imply luminosities  $L \lesssim L^*$  (adopting  $M_K^* = -25.16$  for the local luminosity function of elliptical galaxies; Marzke et al. 1998). In addition, deep HST optical imaging shows that their morphologies are compact and regular, consistent with such ERGs being high- $z$  ellipticals. However, in some cases the SEDs seem to require strong dust extinction to be reproduced (see Fig. 1), and in a fraction of these cases the morphologies are clearly disturbed (i.e. incompatible with being ellipticals). In other cases the required dust may be an artifact of the fitting procedure, in which the metallicity of the population is kept fixed to solar.

On the one hand, our results show the existence of a population of faint galaxies that are selectable through their very red colors and which have properties consistent with the strict definition of being dustless, old and passively evolved spheroidals at  $z > 1$  (see also Spinrad et al. 1997; Soifer et al. 1999). Not surprisingly, our observations also indicate that a non-negligible fraction of the ERG population consists of galaxies whose SEDs and morphologies are more consistent with being high- $z$ , star-forming dusty systems.

The sample for this pilot study is clearly too small to draw more quantitative conclusions at this stage. We now plan somewhat deeper spectroscopic observations of a complete sample, with the aim to assess what fraction of the ERG population consists of passively evolving high- $z$  ellipticals and thus to compare their observed abundance with that expected from pure luminosity evolution models.

## 6. Do Bright Galaxies Disappear by $z \sim 1$ ?

Generally, ellipticals have been selected either according to color or morphological selection criteria, or to some combination thereof. However, as one moves to high redshift, minor residual star formation may cause virtually fully assembled ellipticals to drop out of samples that are selected using color and/or morphological information. To circumvent this limitation, Broadhurst, Ellis, & Glazebrook (1992) proposed to select objects only according to their *K*-band magnitude and

to construct their redshift distribution. This provides a more robust measure of the evolution (if any) of the comoving number density of massive galaxies, and a more fundamental check of the merging paradigm. The advantage of a  $K$ -band selection is that, as opposed to e.g.  $B$ -band selected samples, it favors massive galaxies even if currently experiencing very low levels of star formation.

Following this approach, Kauffmann & Charlot (1998b) estimate that in their pure luminosity evolution (PLE) model  $\sim 60\%$  of the galaxies in a  $K \leq 20$  sample should be at  $z > 1$ , while only  $\sim 10\%$  are expected in a standard hierarchical merging model. The largest redshift surveys of  $K < 20$  selected samples currently available are the Keck samples of Cowie et al. (1996) covering  $\sim 26$  square arcmin, and Cohen et al. (1998) covering  $\sim 14$  square arcmin. Both spectroscopic samples are rather incomplete, for example, the Cohen et al. sample includes 195 objects, among which 24 are stars, 21 are galaxies at  $z > 1$ , and optical spectroscopy failed to provide a redshift for another 32 objects. The vast majority of these latter objects are likely to be galaxies at  $z \gtrsim 1$ , in which major spectral features have moved to the near IR. All in all, in this sample  $\sim 53/171 \simeq 30\%$  of galaxies are likely to be at  $z > 1$ . This empirical value falls (ironically enough) just midway between the prediction of the two competing models. Most importantly, Cohen et al. emphasize that  $\sim 50\%$  of their galaxies fall in just five ‘redshift peaks’ most likely due to clustering. Therefore, a much larger sample is required to dispose of a ‘fair’ representation of the galaxy population, one that is not subject to statistical fluctuations in the number of included large scale structures.

The conclusion is that the two Keck redshift survey of  $K$ -limited samples are so far insufficient to conclude the experiment envisaged by Broadhurst, Ellis, & Glazebrook (1992). Big samples are required, distributed over several different lines of sight so as to average out the effects of clustering and large scale structures. A contribution in this direction will come from an observing program with FORS1, FORS2 and ISAAC at the VLT (PI A. Cimatti), aimed at gathering redshifts of two  $K < 20$  samples over two separate lines of sight, for a total of  $\sim 500$  galaxies.

## 7. Speculations

In the previous sections it has been documented that compelling evidence exists for the bulk of stars in galactic spheroids being very old, i.e. formed at redshifts beyond  $\sim 3$ , and possibly even much beyond this value. This applies to ellipticals and bulges alike, in clusters as well as in the lower density regions still inhabited by spheroids, including the bulge of our own Galaxy. This is what was expected (actually postulated) in the monolithic collapse scenario, while it is at variance with most existing realizations of the hierarchical merging scenario.

The fact that spheroids are made of old stars does not necessarily invalidate the hierarchical merging paradigm, which actually offers a still unique description on how large galaxies could have been assembled. In an effort to comply with the observations, hierarchical models should be tuned to mimic the monolithic model as much as possible, primarily by pushing most of the action back to an earlier cosmological epoch. This is certainly favored by low- $\Omega + \Lambda$  cosmologies, but will not suffice. As universally recognized, the pitfall of semianalytical



realizations of the hierarchical paradigm is represented by how star formation and its feedback are parameterized in the models. The canonical assumption has been that most of the star formation takes place in spiral disks, and ellipticals are formed by merging spirals. We think that this widely entertained paradigm is far from being proven. All we know about ellipticals demands “that star formation, metal enrichment, merging and violent relaxation did not take place sequentially; they more likely were all concomitant processes, along with supernova heating and radiative cooling in a multiphase ISM” (Renzini 1994).

With most of the merging taking place at high redshifts, among still mostly gaseous components, merging itself would promote the widespread starburst activity responsible for the prompt buildup of galactic spheroids (Somerville & Primack 1998; Renzini 1999). The natural observational counterparts of these events may be represented by the Lyman-break galaxies at  $z \gtrsim 3$  (Steidel et al. 1999), where star formation rates could be in extreme cases as high as  $\sim 1000 M_{\odot} \text{yr}^{-1}$  (Dickinson 1998). It remains to be explored whether such tuning of the star formation algorithms and of the many parameters of the semiempirical models could produce model universes fulfilling all other observational constraints.

In this scenario disks are not primordial to spheroids. They rather develop only later, being accreted by those spheroids that happen to be in a permissive environment.

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